Ultra-Lightweight, Ductile Carbon Fiber Reinforced Composites

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Project ID#: mat146

Overview

Timeline

- Project start date: Oct 2018
- Project end date: Dec 2022
- Percent complete: 40%

Barriers and Targets

- **Barrier**: Use of lower-density materials with suitable mechanical properties, i.e., materials with higher strength-to-weight and/or higher stiffness-to-weight ratios.[1)]
- **Target:** Hybrid hierarchical CF reinforced materials that are ultralight, strong and tough for 3D printing.

Budget

- DOE project funding: $500K
  - DOE: 50%
  - Contractor: 50%
- Funding for FY20: $460K

Partners

- Oak Ridge National Laboratory (ORNL)
  Prime contract
  ORNL project lead: Vlastimil Kunc
- Virginia Polytechnic and State University (VT)
  Subcontract
  VT project lead: Xiaoyu (Rayne) Zheng

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[1)] source: 1. U.S. DRIVE MTT Roadmap Report, section 4

Relevance

Overall Objectives

Create hybrid hierarchical materials that are **ultralight**, **strong** and **tough** for 3D printing.

VTO's Mission

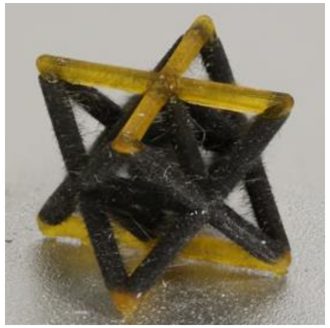
Reduce the transportation energy cost while meeting or exceeding vehicle performance expectations.

Current Limitations

- Lightweight materials: Unsatisfactory strength, toughness and weight density
- Direct deposition: Uncontrollable voids and micro-porosity → Reduced strength and toughness.
- Mutually exclusive properties:
  strength ⟷ toughness
  stiffness ⟷ damping

Our Strategies

- Material Combinations
  - Brittle carbon fiber and multi-material polymers
- Smart Structure
  - Optimal structure **for high stiffness and high damping**



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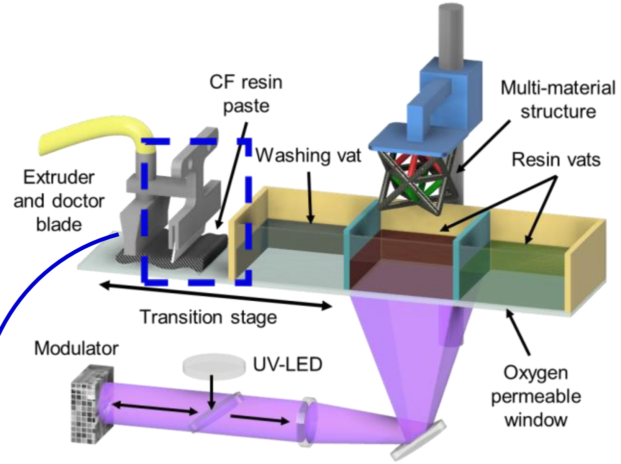
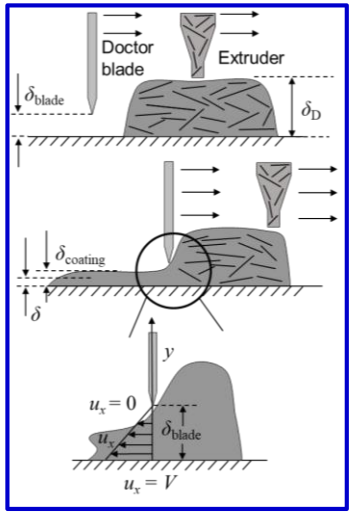
Milestones

Milestone / End Dated	Description	Status
Milestone 1 12/30/2018	Mechanical properties (compression, shear, tensile) verified through theoretical and numerical calculations and experimental testing of microlattice materials	Completed
Milestone 2 9/30/2019	Printing hierarchical two-phase carbon fiber reinforced mesoscale lattice materials, comprised of microscale carbon fiber fillers and large scale structural components.	Completed
Milestone 3 12/30/2019	Size effects of carbon fiber composited printed with varying lengthscales from micrometers to centimeters	Completed
Milestone 4 04/30/2020	Demonstrated ultralight (<200 kg/ m^3) hierarchical carbon fiber composites with tailored energy absorption and high strain recovery (>10%)	Completed
Milestone 5 12/31/2020	Large Area Optical System Setup and Process Characterizations, Multi-material Extrusion System Setup and Material Printing, Demonstrate high resolution CFRP lattice materials with size spans from 10 cm-25 cm	On track
Milestone 6 12/31/2021	Development of moving optics and process optimizations, Integration of moving optics system with multi-nozzle extrusion, Printed multi-material CFRP samples with high damping and stiffness	On track
Milestone 7 12/31/2022	Printing and testing of self-sensing structures, Heating assisted UV curing of high viscosity resin, Achieve optimized layer uniformity and max loading of CFRP fibers	On track

Approach

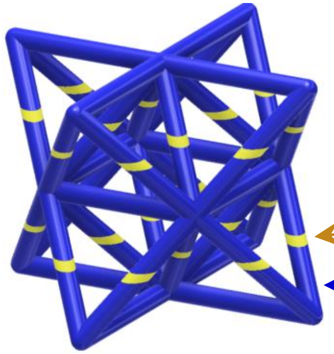
System: Multi-material projection micro-SLA





Recoating a viscous resin (CFRP) with a thin film via the doctor blade

Structure: Lightweight cellular microlattice

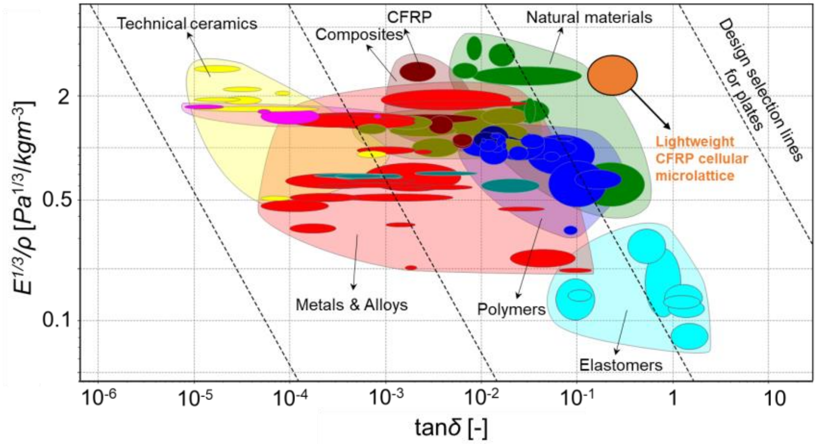


Materials:

(1) Soft material

(2) Stiff CFRP

Measure: damping & stiffness performance of the microlattice $E^{1/3}\tan\delta/\rho$



Using our multi-material PμSL 3D printing system, we aim to design a CF architecture with high stiffness and high damping simultaneously.

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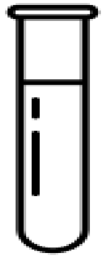
Carbon Fiber Reinforced Polymer (CFRP) Printing

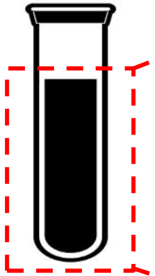


+

Carbon fiber

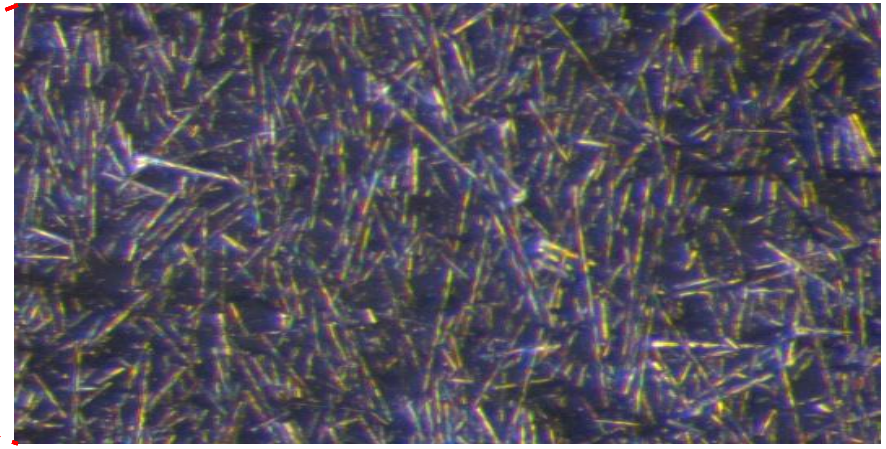
Initiator

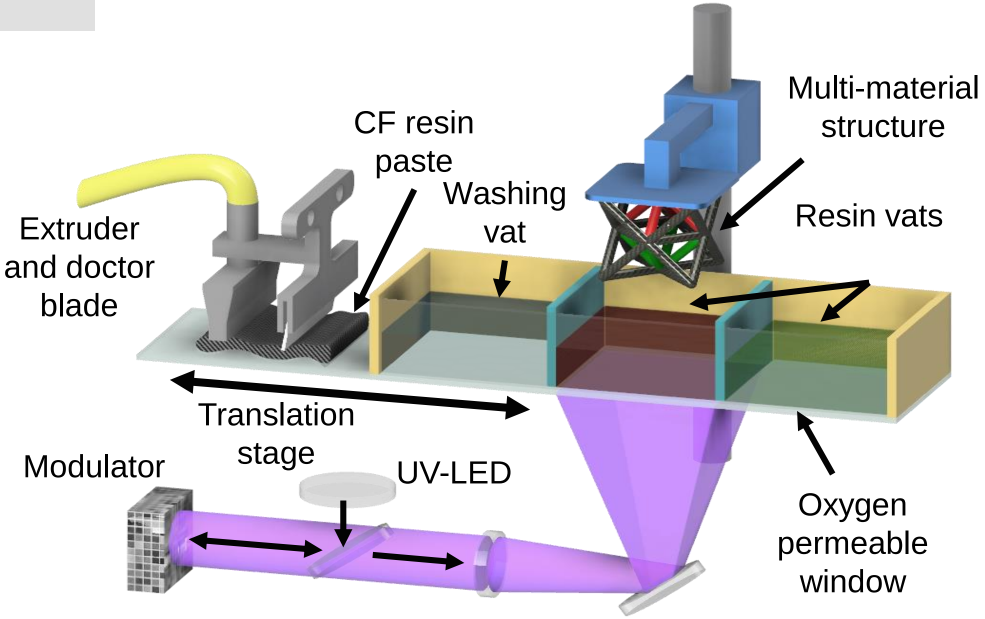
=



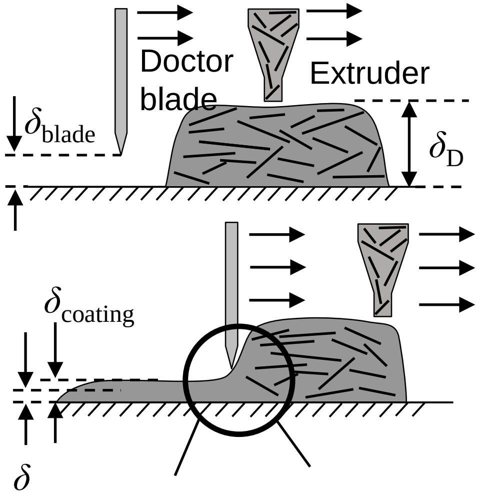
UV curable monomer

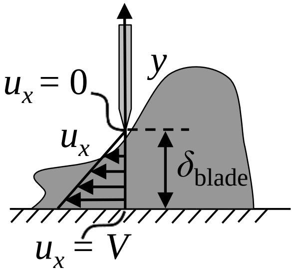
CFRP





Multi-material projection microstereolithography (PµSL) system

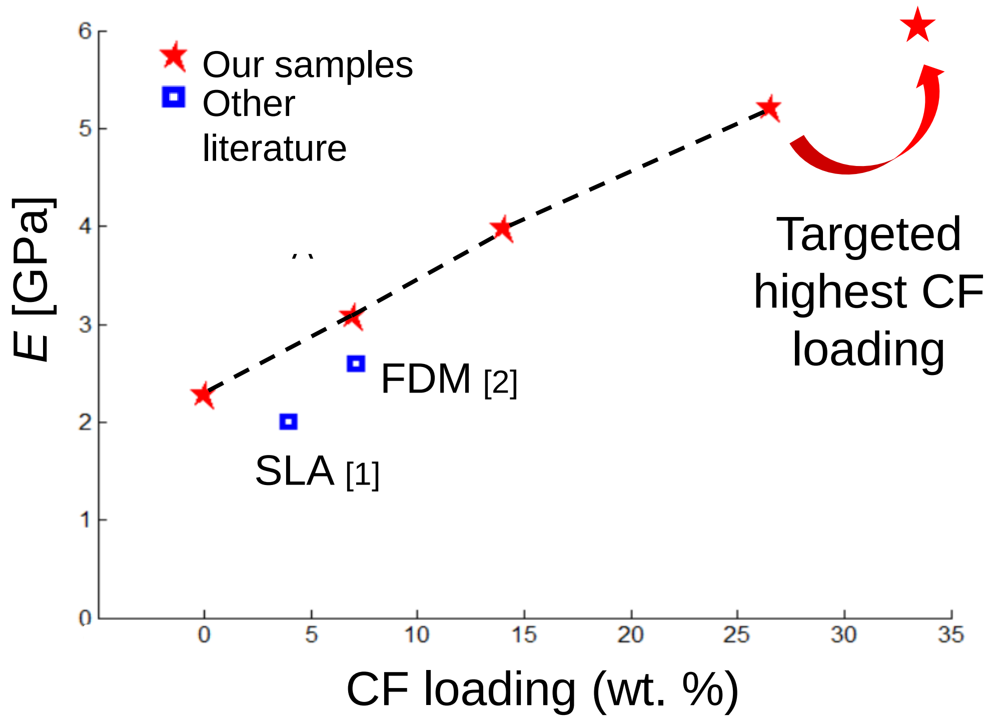


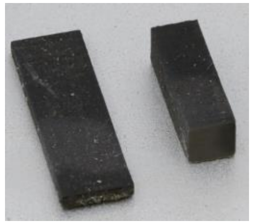


We developed PµSL 3D printing system that can fabricate samples with carbon fiber reinforced polymer (CFRP) with a resolution of ~50 microns.

CFRP Stiffness with CF Loading and Relative Density

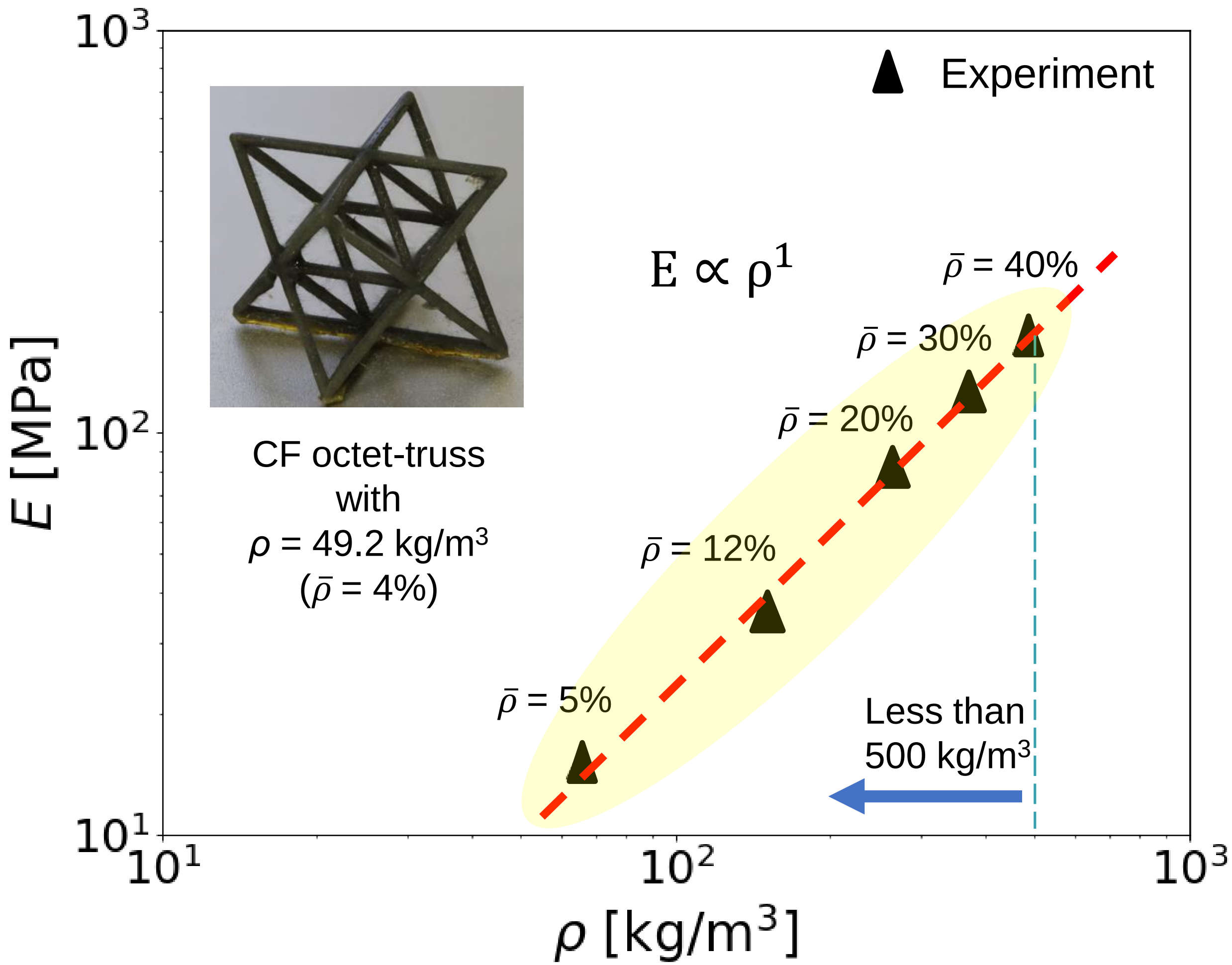
Comparison of elastic tensile modulus of CFRP





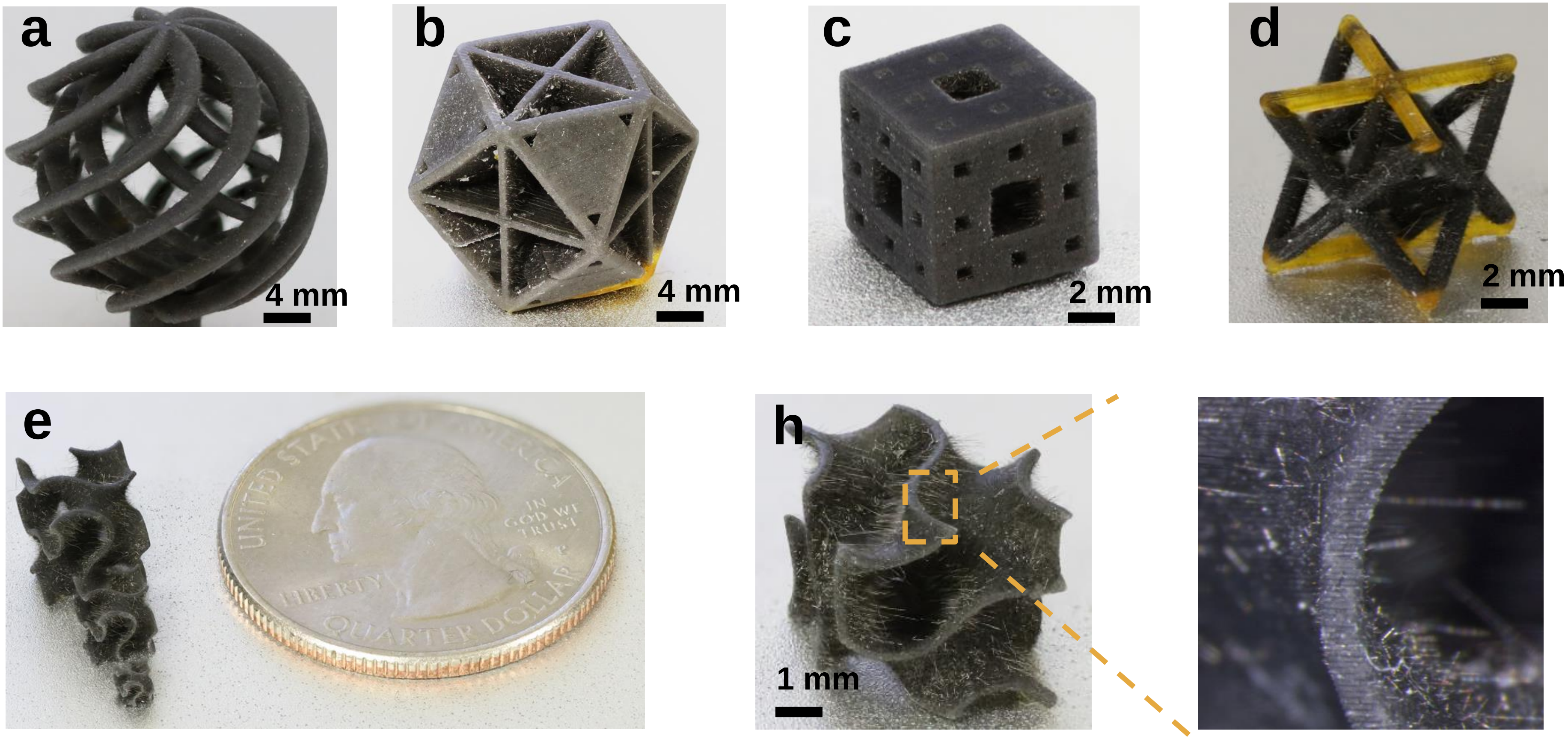
7.5wt% Bulk samples

27wt% CF loading dog bone



The target CF loading in our CFRP material is higher than other commonly used samples.

Lattice Structure



We choose octet-truss geometry because:

- Lightweight
- Favorable E-ρ relationship
- Stretch-dominated ($E \sim \rho^1$)
- Greater stiffness per unit weight than bending-dominated

Complex 3D structures fabricated by our PμSL printer using CFRP. (a) Spiral ball. (b) Closed foam. (c) Cube with holes. (d) Multi-material octet-truss made of CFRP and polyethylene glycol diacrylate (PEGDA) resin. (e-h) arbitrary gyroid 3D structure with a minimum feature of ~150μm

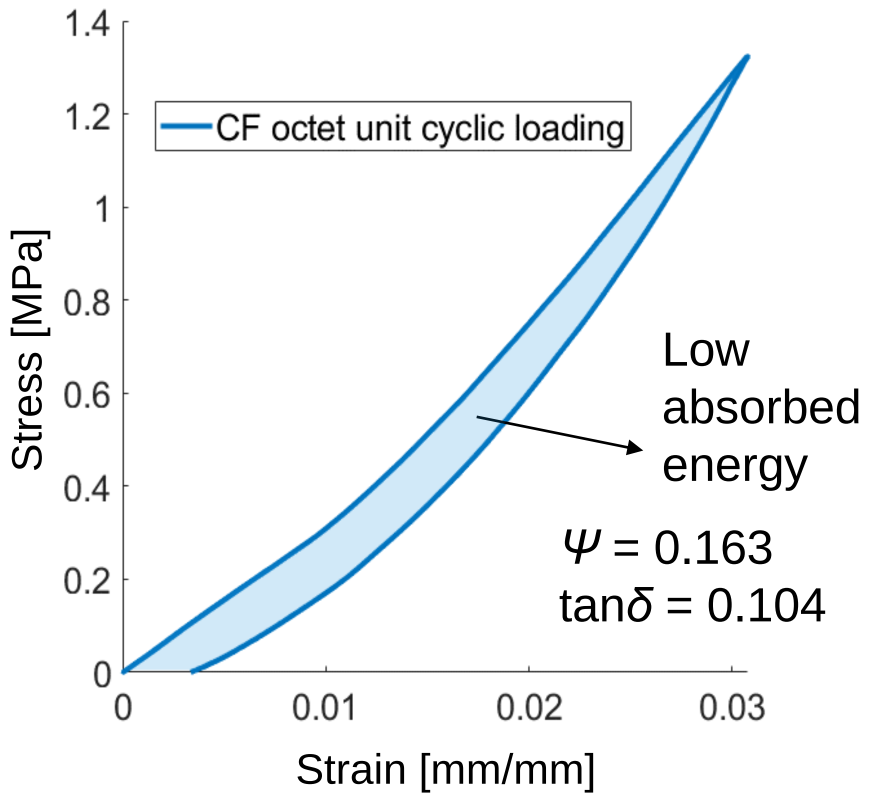
Achieved CF composites with complex 3D micro-architectures with multi-materials.

Intrinsic/Structural Damping for Lattice Structure

Intrinsic damping

tanδ (at 10 Hz) = 0.038 via DMA test

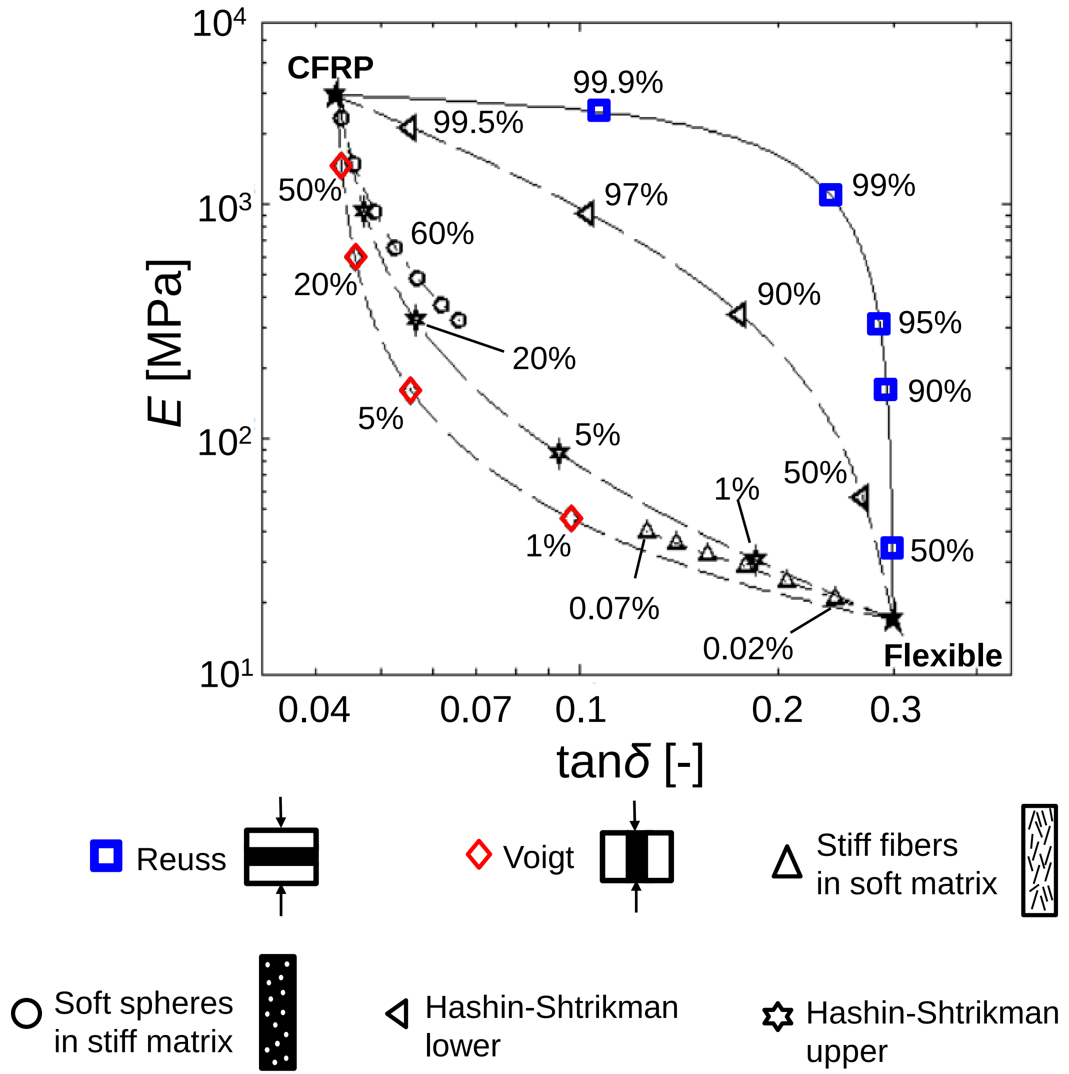
Structural damping



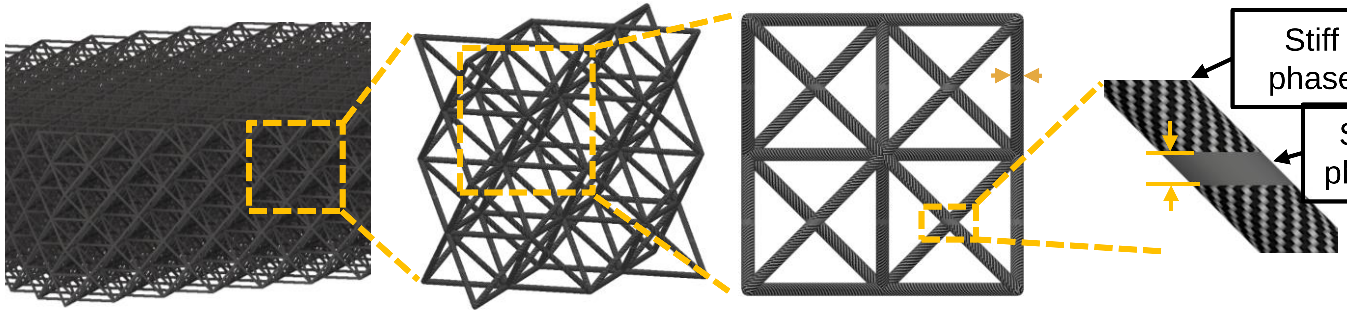
	Intrinsic damping	Structural damping
Range	Infinitesimal or small	Large
Cause	Viscoelastic nature of material itself	Deformation mechanisms of constituent cells
Testing method	Dynamic Material Analysis (DMA)	Quasi-static cyclic tests using screw-driven test frame
Measure	E', E'', tanδ	E^*, U, ΔU from σ-ε hysteresis loops
Important equations	$\tan\delta = \frac{E''}{E'}$	$\psi = \frac{\Delta U}{U} = \frac{\pi}{2}\tan\delta$ $\Delta U = \oint \sigma\, d\epsilon\, , U = \int_{\omega t=0}^{\omega t=\pi/2} \sigma\, d\epsilon$

Energy dissipation through intrinsic damping and structural damping

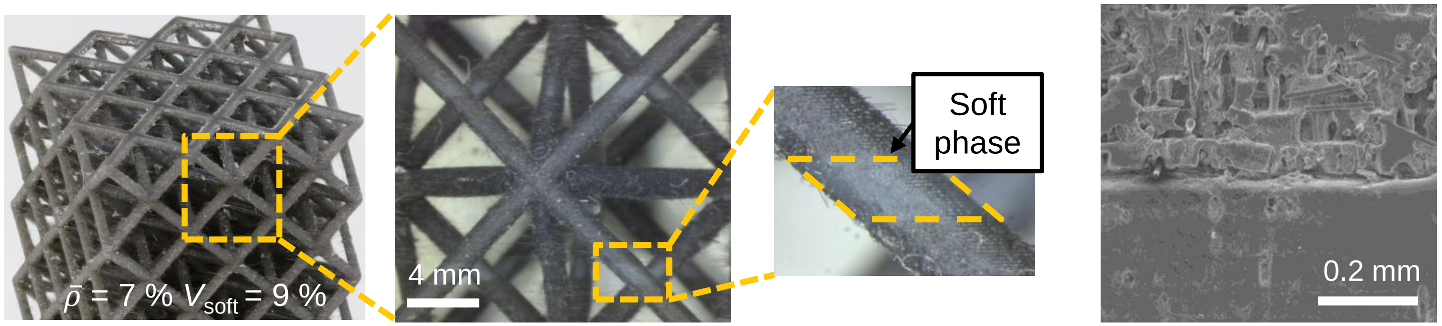
Intrinsic Damping of Bulk CFRP with Soft phase



Design of lightweight, stiff, high damping microlattice with two-phase materials incorporating CFRP and soft phase

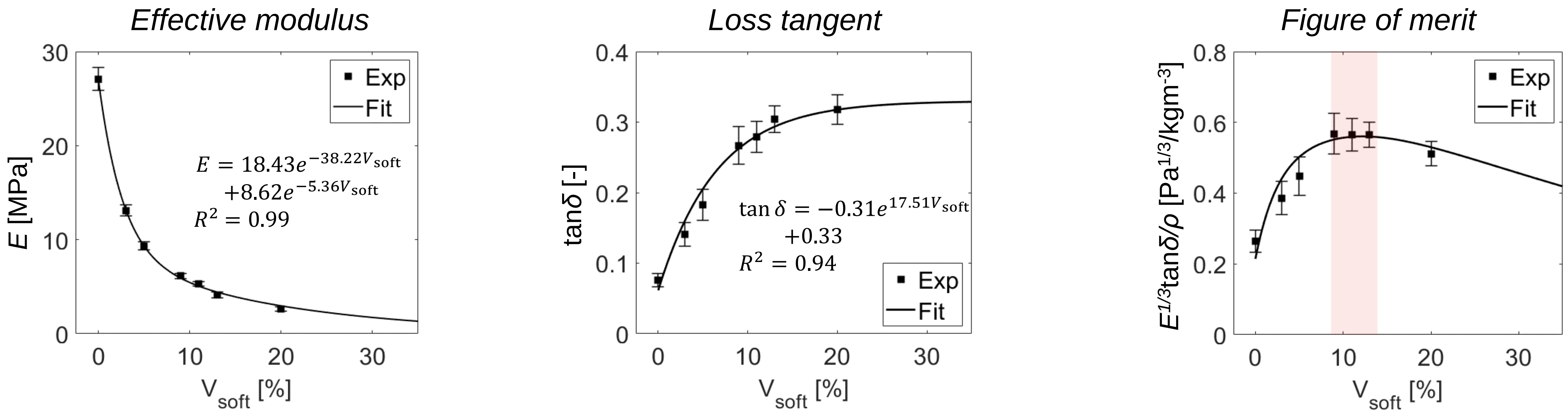


Fabricated lightweight cellular CFRP microlattice having $\bar{\rho}$ = 7 % with V_{soft} = 9 %



We adopted a two-phase design comprising solid CF reinforced composite and soft material to reach the upper bound of stiffness-damping pair

Intrinsic Damping (Experiment)

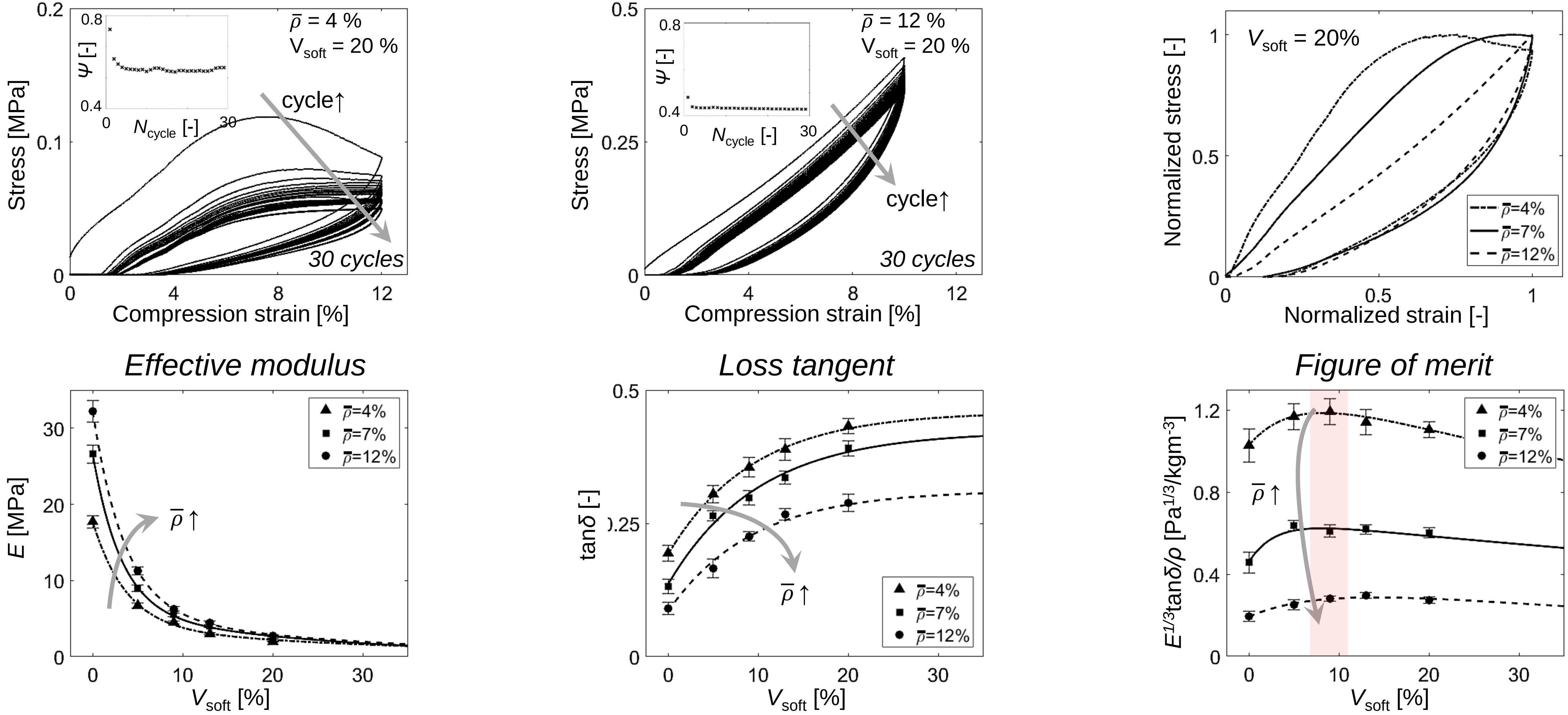


- Results shown for our CFRP microlattice of $\bar{\rho}$ = 7 %
  - Intrinsic damping properties are independent of relative density by theory
- As an increase in V_{soft}, E decreases and tanδ increases
- At near V_{soft} ~ 10 %, damping FOM (3rd figure) becomes the maximum, which is ~3 times larger than that of pure CFRP lattices

Theoretical prediction shows that the optimal (= maximum) figure of merit can be achieved at V_{soft} = 10% from intrinsic damping.

Structural Damping (Experiment)

Evolution of stress-strain hysteresis with various $\bar{\rho}$ under cyclic loading

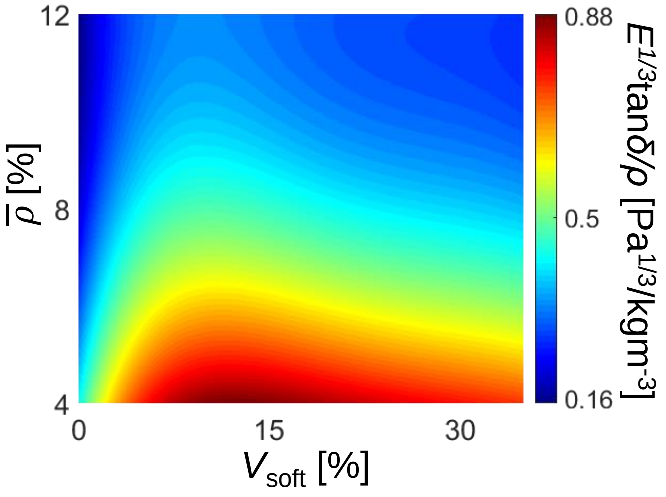


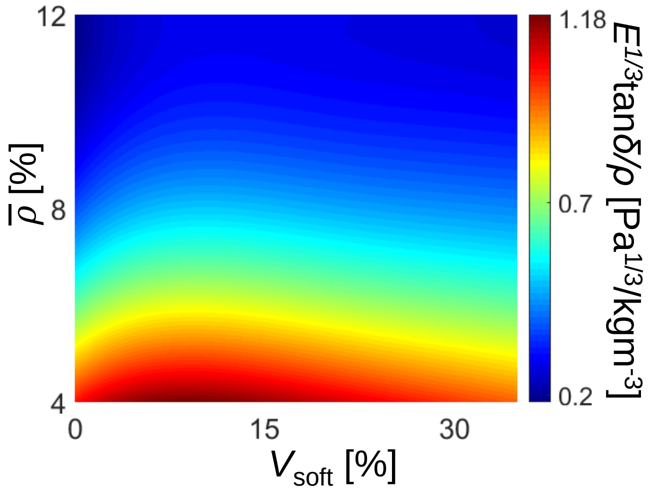
- Improved damping performance in low relative densities
- Peaks of $E^{1/3}\tan\delta/\rho$ at V_{soft} ~ 10 %

Our CFRP microlattice at low relative densities is desirable to maximize damping performance for a specific volume fraction of soft material.

Tunability Maps & Performance Chart

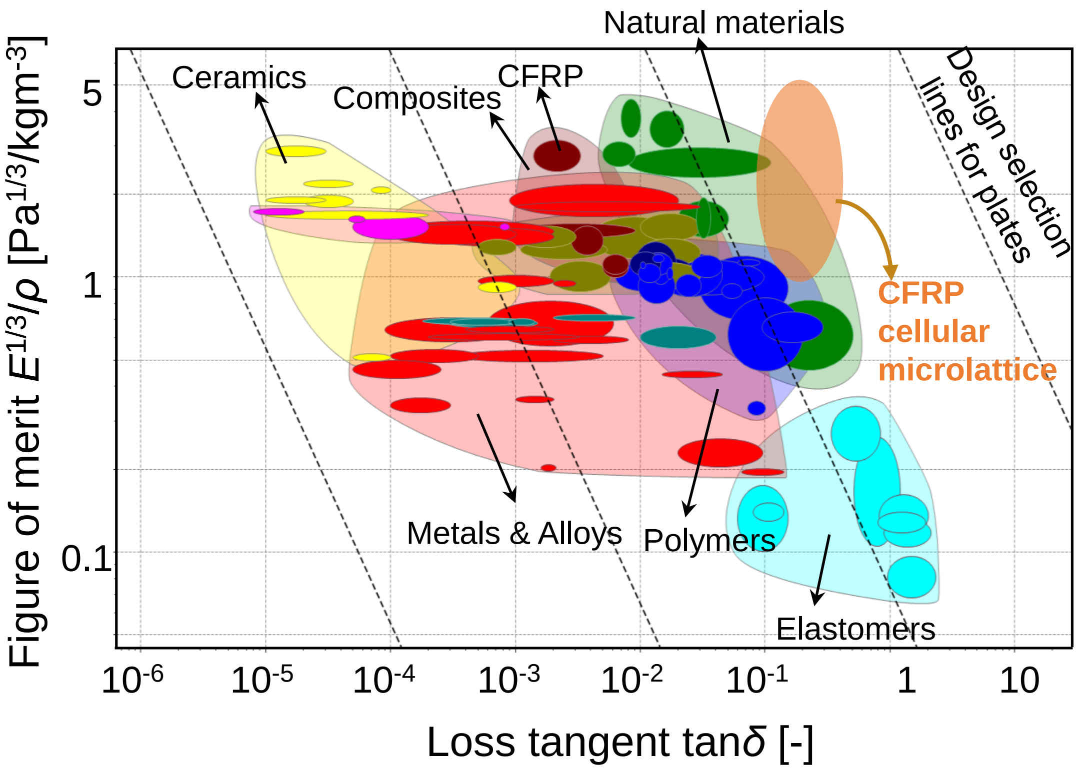
Tunability maps of the damping figure of merit





- Tunability maps are based on experimental measurements and inter/extrapolation
- The maps offer to choose a specific set of design parameters for the desired stiffness-damping pair.

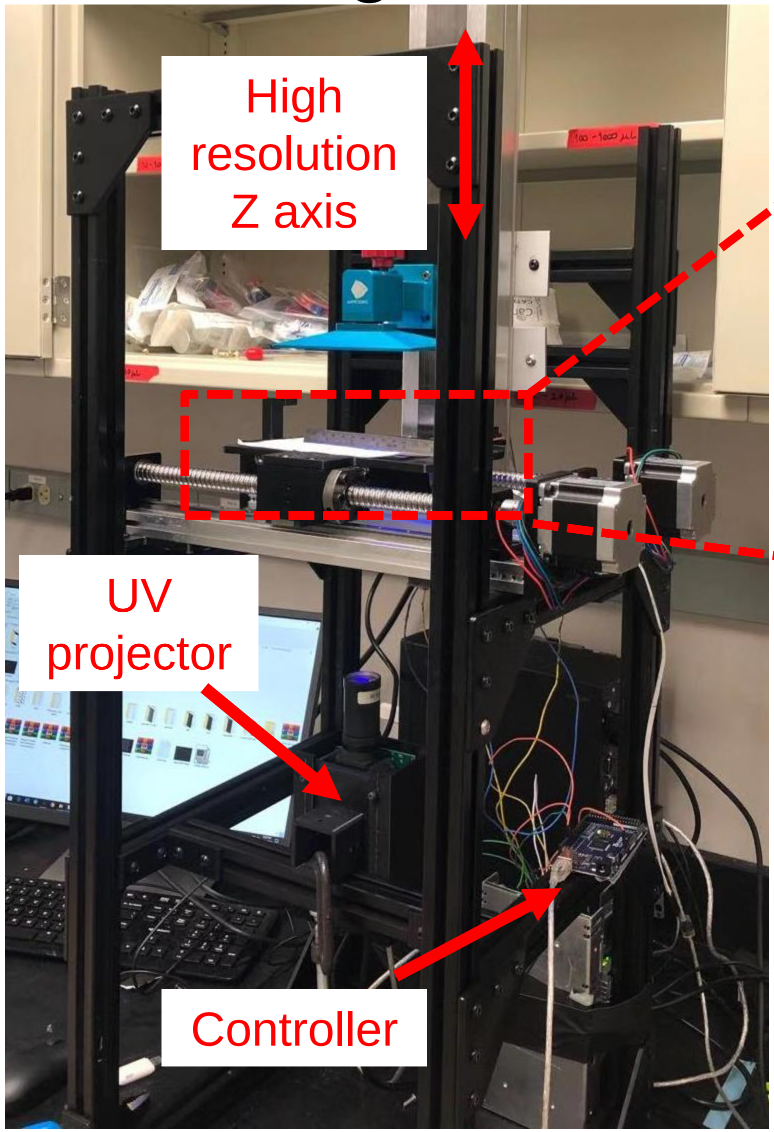
$E^{1/3}/\rho$ vs. tanδ chart for our lightweight cellular CFRP microlattice and other family of materials

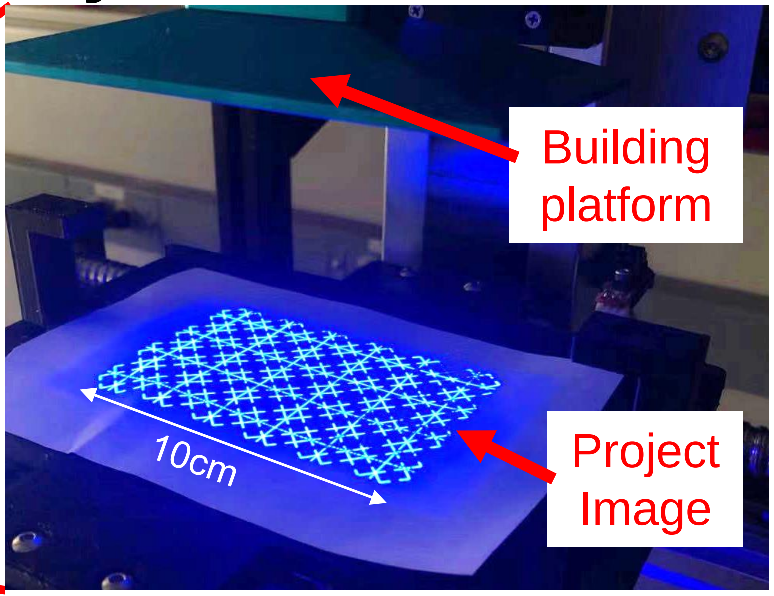


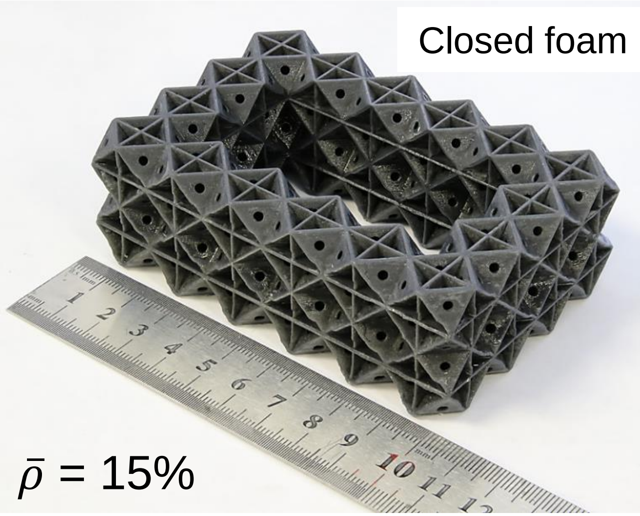
- Our CFRP microlattices have specific stiffness comparable to commercially available CFRP while being dissipative as elastomers.

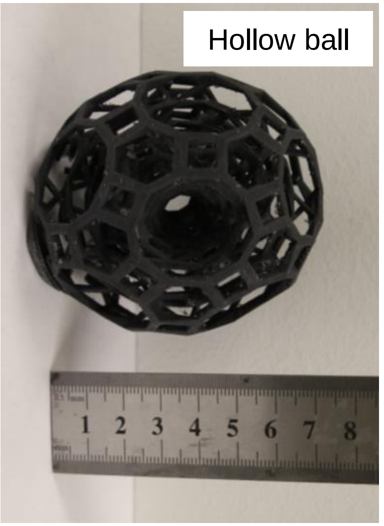
Design of our CFRP microlattice offers tunability for the desired stiffness-damping pair.

Large Area CF Printing System





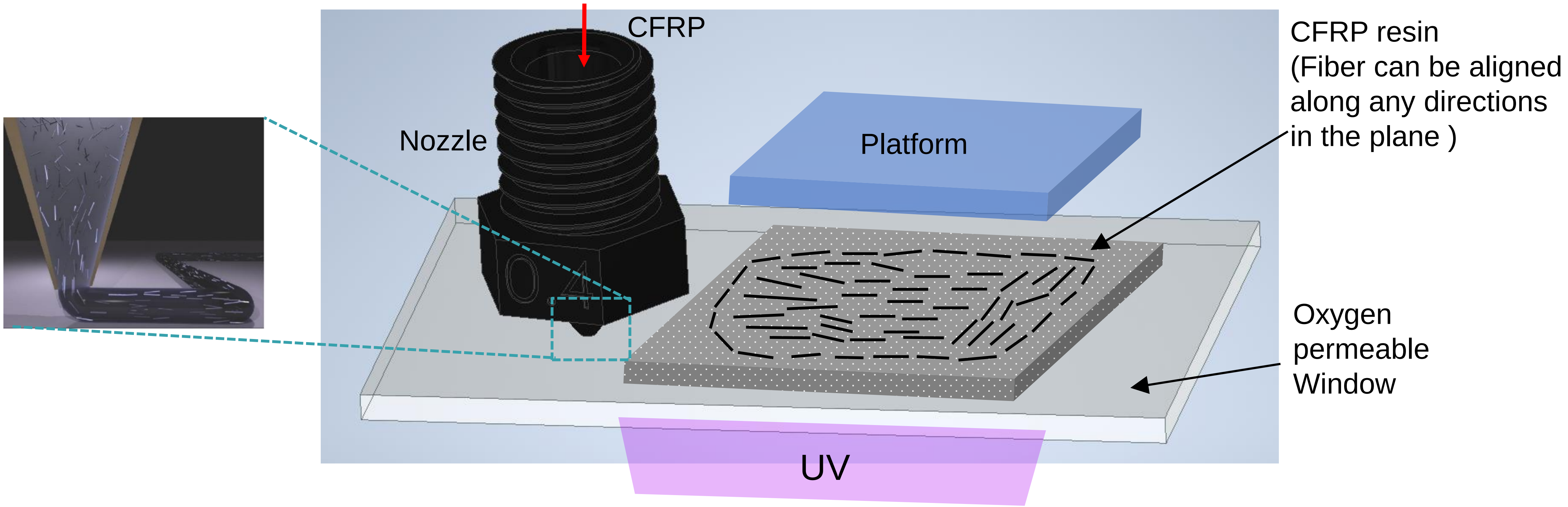




Printing dimension: ~ 12 x 8 x 7 (cm^3)

We improved our PμSL system with adjustable printing area to fabricate large-scale CFRP lattice structures.

Proposed Method for Carbon Fiber Alignment

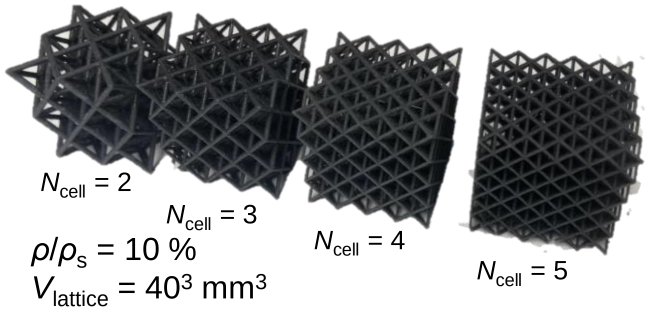


Stereolithography integrated with extrusion process

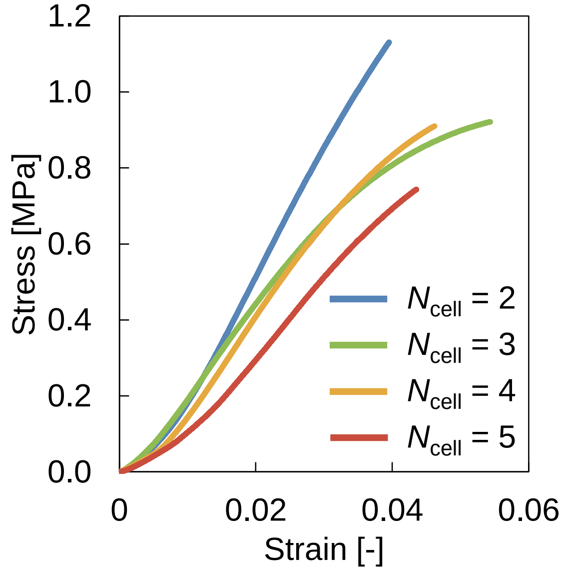
We propose a method for carbon fiber alignment via stereolithography integrated with extrusion process, offering superior resolution (~0.1 mm).

Size effects of CFRP octet-truss

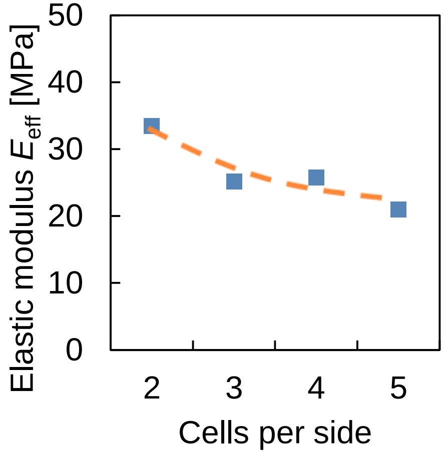
CFRP octet-truss lattices



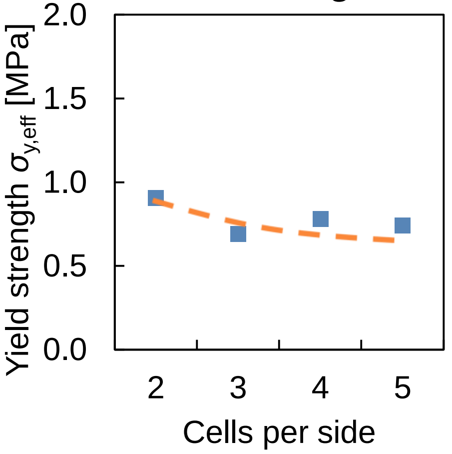
Quasi-static, compressive stress-strain behaviors



Elastic modulus



Yield strength



- Our large area PμSL system enables sample fabrication with varying lengthscales from micrometers to centimeters.
- Results shown for CFRP microlattices with different number of cells while the relative density and the overall volume kept constant.
- Both elastic modulus and yield strength revealed softening size effects.
- This size effect was due to boundary condition-induced, localized stress concentrations.

We observed softening size effects on material properties of CFRP octet-truss lattice structures.

Collaboration

- Subcontractor: University of California, Los Angeles
  - Xiaoyu Rayne Zheng, Zhenpeng Xu, Chan Soo Ha

Remaining Challenges

- Develop higher modulus carbon fiber reinforced polymer composites
  - Choose a monomer with lower viscosity to increase fiber loading of CFRP.
  - Managing viscosity and processability: viscosity of the resin increases as carbon fiber loading increases.
- Tradeoff between resolution and building area
  - Scaling up printing method in progress.
- Scale up of technology for vehicle demonstration
- Achievement of superior recoverability (>20%) with the brittle nature of carbon fiber composite

Proposed Future Research

Ongoing:

- Design hierarchical carbon fiber lattice materials (< 500kg/m3) with tunable directional or isotropic functionally graded designed stiffness and energy absorbing capabilities.

Planned:

- Large Area CFRP Smart Composite Additive Manufacturing (Resolution <50μm, >25 cm x 25cm)
- Additive manufacturing of CFRP composite with aligned carbon fiber arrays
- Additive Manufacturing of Smart Composites (Self-sensing)
- Additive manufacture lightweight carbon fiber lattice materials (< 100kg/m3 with <100 microns feature size) with superior recoverability (>20% in strain).

Any proposed future work is subject to change based on funding levels.

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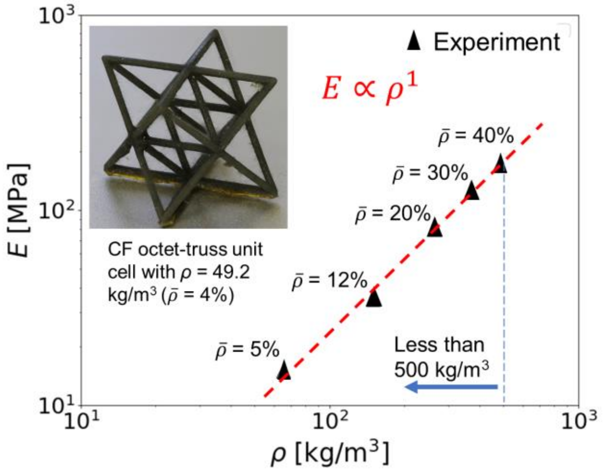
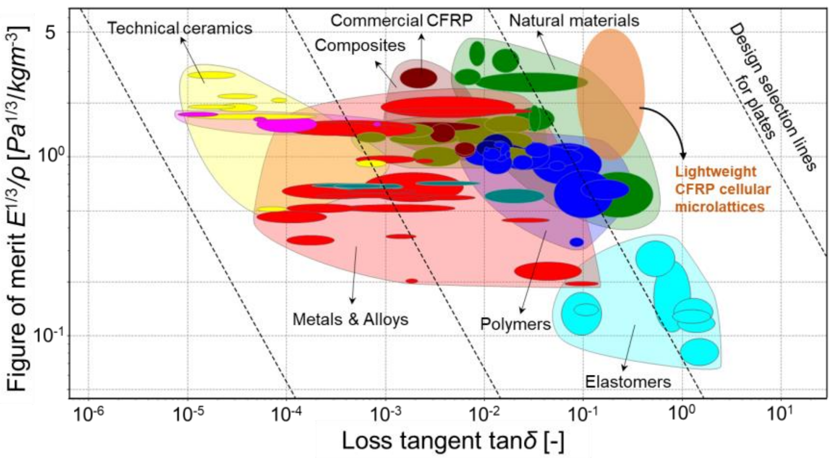
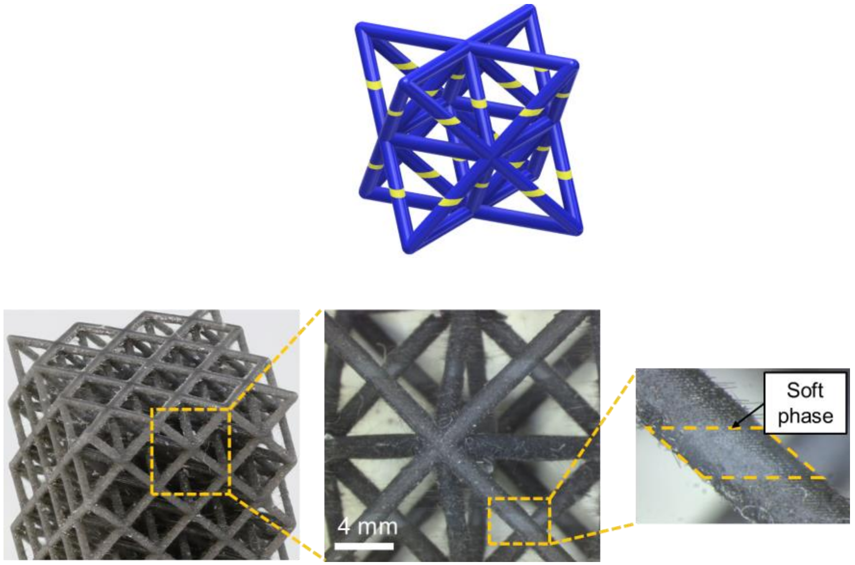
Summary

- Target: Hybrid hierarchical CF reinforced materials that are ultralight, strong and tough for 3D printing.
- Developed: Multi-material lattice structures with high stiffness, high damping / energy absorption and high strain recovery (>10%)
- Future: Fabricate hierarchical carbon fiber lattice materials (<500kg/m3) with tunable directional or isotropic functionally graded designed stiffness and energy absorbing capabilities with superior recoverability (>20% in strain)







Publication

[1] Xu, Z., C. Ha, R. Kadam, J. Lindahl, S. Kim, Felix Wu, V. Kunc, and X. Zheng, “Additive Manufacturing of Two-Phase Lightweight, Stiff, and High Damping Carbon Fiber Reinforced Polymer Microlattice”, Additive Manufacturing, 32, 101106 (2020).

Reference

[1] G. D. Goh et al., Recent Progress in Additive manufacturing of polymer reinforced composites, Advanced materials, 4 (1), 1800271 (2019).

[2] F. Ning et al., Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling, Composite part B: engineering, 80, 369-378 (2015).

[3] X. Zheng et al., Ultralight, Ultrastiff Mechanical Metamaterials, Science, 344 (6190), 1373-1377 (2014).

[4] B. G. Compton and J. A. Lewis. 3D-printing of lightweight cellular composites. Advanced materials, 26 (34), 5930-5935 (2014).

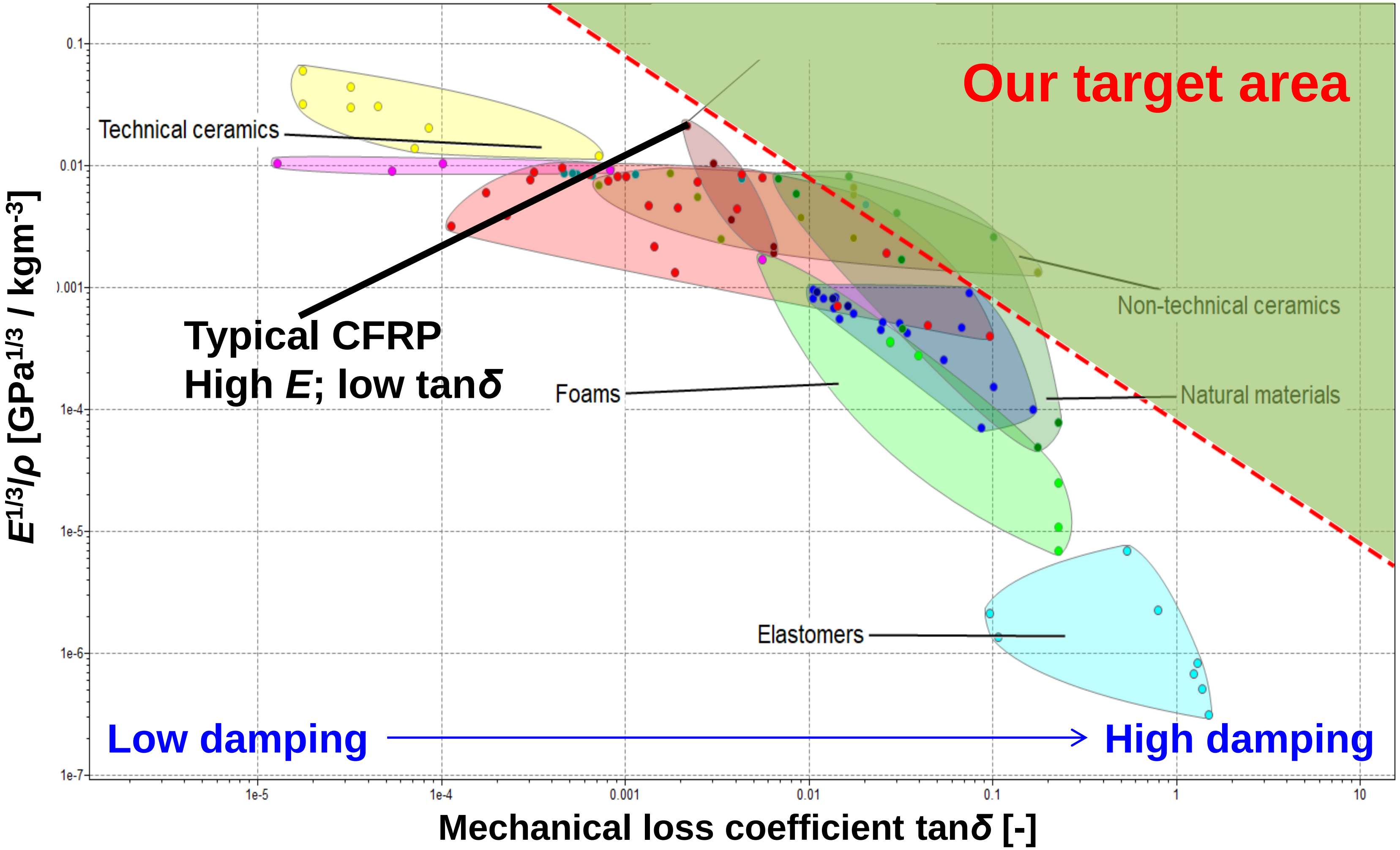
[5] Y. Watanabe, Evaluation of fiber orientation in ferromagnetic short-fiber reinforced composites by magnetic anisotropy. Journal of composite materials, 36 (8), 915-923 (2002).

[6] B. P. Heller, Effects of Nozzle Geometry and Extrudate Swell on Fiber Orientation in Fused Deposition Modeling Nozzle Flow, Doctoral dissertation, Baylor University (2015).

Back Up Slides

Design Goal

- Maximize the figure of merit, $E^{1/3}\tan\delta / \rho$

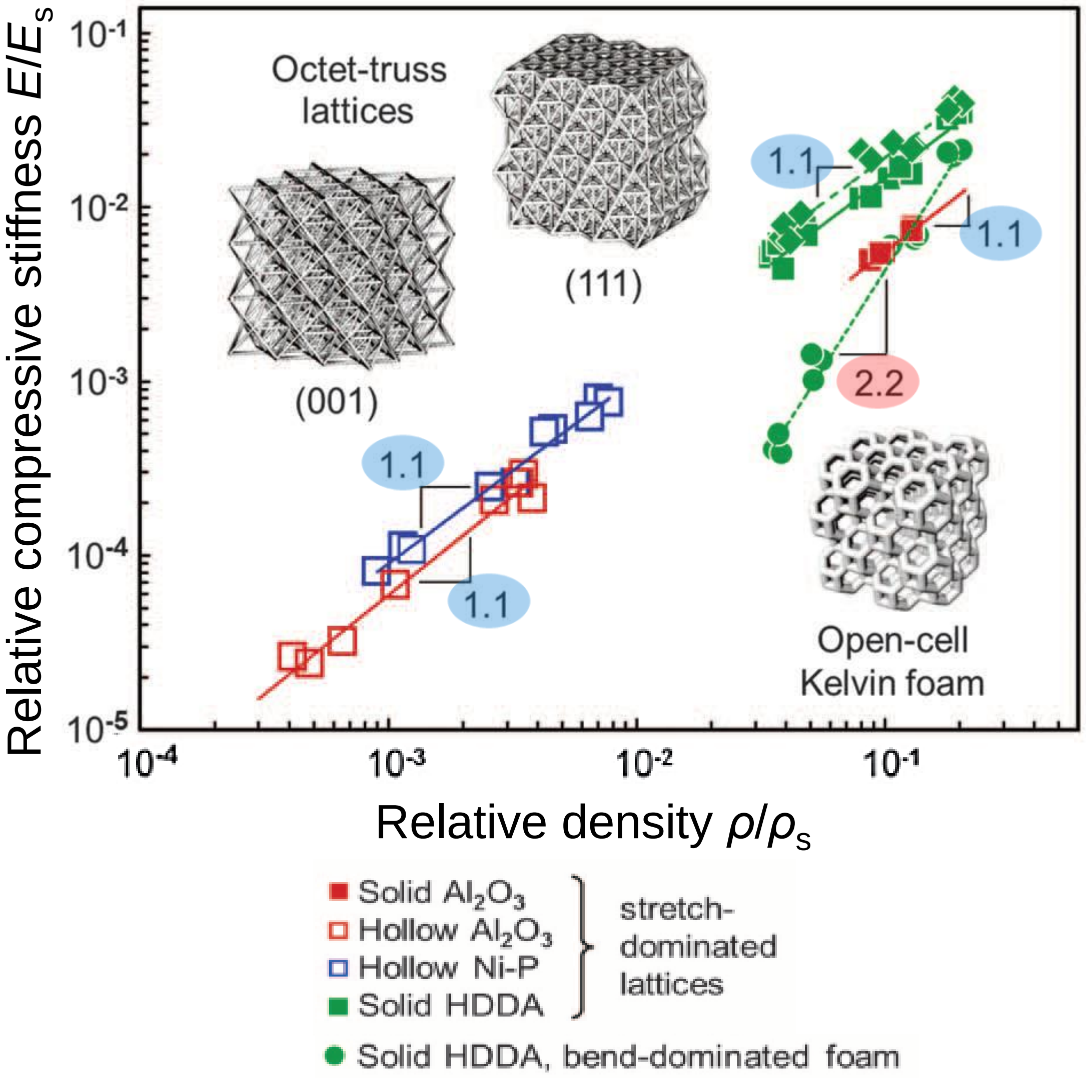


$E^{1/3}/\rho$ vs. $\tan\delta$ chart for CFRP and other family of materials

Using our multi-material PμSL 3D printing system, we aim to design a CF architecture with high stiffness and high damping simultaneously.

Lightweight, High-Stiffness Microlattice

Adopted from Ref [3]



We choose octet-truss geometry because:

- Lightweight
- Favorable E-ρ relationship
- Stretch-dominated ($E \sim \rho^1$)
- Greater stiffness per unit weight than bending-dominated

We selected octet-truss unit cell as a base architecture due to its lightweightness and its greater stiffness per unit weight than bending-dominated cells.